Design and Operation of the Miniature Vector Laser Magnetometer

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Abstract - **The Miniature Vector Laser Magnetometer (MVLM) is a high accuracy instrument that will permit distributed measurements of the magnetic field components in the near Earth environment. The MVLM design incorporates both scalar and vector modes that each extract magnetic field information from a single laser-pumped helium cell sensor. The scalar mode accuracy is determined by an atomic constant and is used to perform in-flight calibration of the instrument in order to achieve an accuracy of 1 part in 100,000. The MVLM measures static and time-varying magnetic field components over the range of +/-100,000 nT with a sensitivity of 10 pT per root Hertz and an accuracy of +/-1 nT. The instrument is currently in the second year of development under the NASA Instrument Incubator Program.**

I. INTRODUCTION

The accurate measurement of the ambient magnetic field vector and its orientation in space has been recognized as a basic requirement for Earth science research. The Miniature Vector Laser Magnetometer (MVLM) sensor uses a helium absorption cell that measures three orthogonal components of the local field referenced to an inertial coordinate system. A scalar mode is also implemented which measures the magnitude of the ambient field with intrinsically high accuracy. The accuracy is determined by an atomic constant and can be used as a reference for calibrating the vector mode measurements.

The MVLM is capable of measuring magnetic fields over a large dynamic range of ±100,000 nT. The instrument has lower volume, mass, and power requirements than previous helium magnetometers and better stability than fluxgate magnetometers. In addition, the sensor has no permeable materials and operates over a wide temperature range. The sensor is also resistant to the destructive effects of intense radiation from solar flares and energetic trapped particles in the magnetosphere.

The instrument specification calls for a magnetometer with uncommon accuracy, sensitivity, stability, and dynamic range to meet the scientific and environmental requirements of future Earth science missions. These goals are achievable by implementing the proven helium magnetometer sensor design with state-of-the-art digital electronics and utilizing the proprietary laser pump source developed by Polatomic [Slocum, 1991 - U.S. Patent 5,036,278].

Single-line laser pumping in helium allows cell miniaturization without loss of sensitivity. The 6 cm^3 laser pumped helium cell used in the MVLM has better sensitivity than the 48 cm^3 lamp pumped cell used in previous helium magnetometers such as the SAC-C instrument. Reduction of cell size also allows miniaturization of the other associated components in the sensor. The laser pump source allows further sensor miniaturization by moving the pump source from the boom-mounted sensor into the electronics package in the spacecraft equipment bay and utilizing fiber-optic technology to transfer the pumping radiation. Laser pumping also offers the opportunity of extracting high accuracy scalar information from the same miniature helium cell which can be used as a reference for calibrating the vector mode measurements. The scalar mode function is currently being developed under a NASA/JPL SBIR Phase II contract and will be integrated into the MVLM instrument during Year 3 of the NASA Instrument Incubator Program.

II. OPERATING PRINCIPLES

A. Optical Pumping

The MVLM utilizes a helium cell sensing element and its operation is based on the principles of optically pumped He^4 in the metastable triplet state. An abbreviated energy level diagram for helium is shown in Fig. 1. Helium atoms in the 1^1S_0 ground state are excited by a weak RF discharge to the 2^3S_1 metastable level. In the presence of an external magnetic field, Zeeman splitting separates the 2^3S_1 level into three substates m= 0, ±1. Helium gas is optically pumped when absorbed D_0 radiation at 1082.91 nm is used to change the 2^3S_1 metastable level population from an equal distribution over the magnetic substates to an unequal distribution.

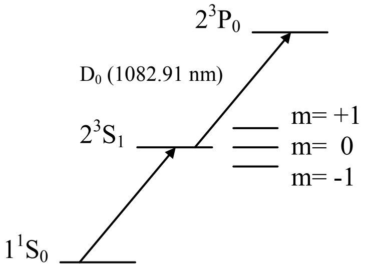

Fig. 1. Energy level diagram for helium.

This is accomplished by using circularly polarized radiation, which is preferentially absorbed by atoms in the m = -1 state. These atoms are transferred to the m = 0, +1 states by re-radiation from the 2^3P_0 level. This creates a population difference between the m = ±1 states, and thereby creates a net magnetic moment in the gas. Magnetic field information is obtained by observing field dependent changes in the optical density of the optically pumped helium state distribution. The disturbance of the pumped state is detected by focusing the laser pumping light onto an IR detector and observing the intensity variation as pumping occurs.

B. *Vector Mode*

The functional block diagram for vector mode is shown in Fig. 2. Laser pumping radiation at 1083 nm passes through a circular polarizer to a He^4 absorption cell which contains metastable atoms produced by a weak RF discharge. An external ambient magnetic field H_A causes Zeeman splitting to occur and the circularly polarized pumping light produces an orientation in the metastable helium with a net magnetic moment. The emergent radiation is detected by an IR detector, the output of which is a measure of the absorption in the cell. A three-axis Helmholtz coil system surrounding the cell is used to apply rotating sweep fields H_S commutated in two orthogonal planes about the sensor which modulate the absorption in the cell.

The absorption of the laser radiation is proportional to a function which is closely approximated by $\sin^2\theta$, where θ is the angle between the rotating magnetic vector and the light beam. The absorption is thus modulated at the second harmonic of the sweep frequency. When a steady or slowly varying ambient magnetic field H_A is encountered, the absorption is modulated at the second harmonic plus the fundamental of the sweep frequency. Synchronously detecting the fundamental provides the error signal required to null the field at the absorption cell. The phase demodulator creates a bias current I_B which is applied to the coil system along with the sweeps. The bias field H_B nulls the ambient field H_A.

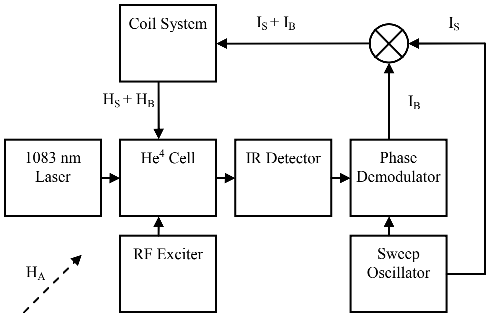

Fig. 2. Vector laser magnetometer concept of operation.

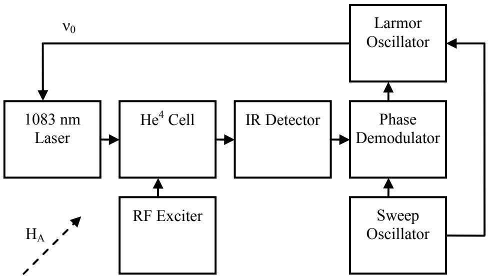

Fig. 3. Scalar laser magnetometer concept of operation.

The resulting bias currents provide measurements of the three vector components of the ambient magnetic field. The first use of this bias field nulling (BFN) method in an optically pumped low-field vector helium magnetometer was reported by Slocum and Reilly [IEEE Trans. on Nuclear Science NS-10, 165 (1963)].

C. *Scalar Mode*

Absolute calibration of the vector magnetometer utilizes a scalar field measurement and employs the advanced resonance technique of optically-driven spin precession (OSP). The functional block diagram is shown in Fig. 3. As in vector mode, the operation of scalar-mode is based on the principles of optically pumped He^4 in the metastable triplet state. The magnetic field in this case is measured by tracking the Larmor precession frequency ν_0 associated with the Zeeman splitting that occurs in the optically pumped helium.

The efficiency of optical pumping is maximum and the absorption is minimum when the frequency of the pulsed laser radiation is at the Larmor frequency. The Larmor frequency for metastable He^4 is directly proportional to the ambient magnetic field with a proportionality constant of $\gamma_e/2\pi = 28.0249540$ Hz/nT, where γ_e is the electron gyromagnetic ratio.

The scalar feedback loop is a null sensing control loop as is the vector control loop. The scalar electronics detect and track the Larmor frequency as compared to the vector electronics that detect and track an error resulting from the addition of the sweep field and the ambient field. Since the Larmor frequency is based on fundamental constants, the scalar's absolute accuracy is about 100 times better than that of the vector measurement. Tracking the Larmor frequency is accomplished by frequency modulating the pulsed laser radiation at an audio frequency. When the control loop is exactly at the Larmor frequency only the second harmonic of the audio frequency is detected. The addition of a steady or slowly varying magnetic field generates a fundamental of the audio frequency along with the second harmonic. Synchronously detecting the fundamental generates an error signal to draw the control loop back to the Larmor frequency. The scalar mode function is currently being developed under a NASA/JPL SBIR Phase II contract

III. INSTRUMENT DESCRIPTION

The instrument consists of two packages: the Electronics Unit (EU) located in the spacecraft equipment bay and the boom-mounted Sensor Unit (SU). They are connected by a boom cable (typically 6-8 meters) which carries the ignition signal, RF exciter signal, coil drive signals, laser optical fiber, and detector optical fiber. Components and materials are being selected to allow transition to radiation-hardened parts and to minimize the generation of magnetic fields that affect measurements. Because of the MVLM sensitivity, the boom is required to place the sensor away from the main body of the spacecraft. Magnetic cleanliness of the spacecraft reduces the boom length requirements.

The dimensions of the Electronics Unit are 15 x 20 x 6 cm with a mass of 1.8 kg. The Electronics Unit, shown in Fig. 4, generates the ignition pulses and RF power used by the helium cell, creates and detects the laser pumping radiation, and drives the sensor coils. It also processes the signals from the sensor, controls the instrument operating modes, and formats all the science and engineering data for processing by the spacecraft data subsystem. The Electronics Unit consumes less than 5 watts. The temperature of the Electronics Unit is controlled by the thermal environment of the spacecraft.

The dimensions of the Sensor Unit are 6 x 6 x 12 cm with a mass of 0.6 kg. The sensor dissipates 100 mW of RF power in maintaining the RF discharge in the cell and 100 mW in the coil windings. An insulating thermal blanket and a heating unit are required to control the sensor temperature over widely-varying thermal environments. Temperature control of the sensor is managed by the spacecraft resources. The sensor temperature is transmitted to the EU control system over the spacecraft interface bus.

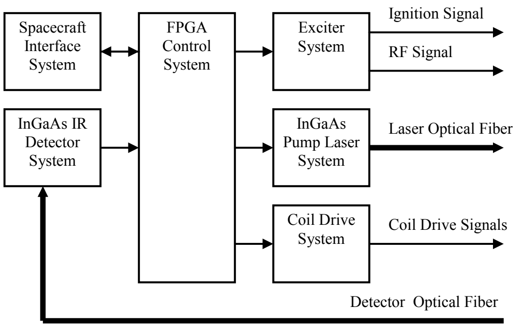

Fig. 4. MVLM Electronics Unit (EU) block diagram.

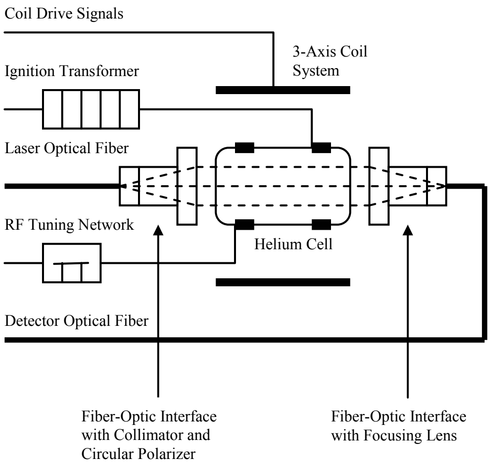

Fig. 5. MVLM Sensor Unit (SU) functional diagram.

Fig. 5 is a functional diagram of the sensor components. At instrument turn-on a 50 kHz ignition signal is triggered and is transformed to 2000 V_{pp} by the air-core transformer in the sensor to initiate the cell discharge. The discharge is maintained by 100 mW of 27 MHz RF power which is matched to the cell by the tuning network. The ignition voltage and RF power are capacitively coupled through copper bands on the helium cell. The cell discharge level is set by the control system for approximately 10% absorption when the ambient field is aligned with the optical axis.

The fiber-optic 1083 nm collimated laser radiation passes through a linear polarizer and quarter-wave retarder to form the circular polarized pumping light. The radiation passes through the helium cell and is focused onto the fiber-optic interface for the detector optical fiber.

The InGaAs diode laser wavelength and power output are controlled with temperature and current. The laser heatsink environment in the spacecraft keeps the temperature within the dynamic control range of the internal thermoelectric cooler. The control system sets the laser current and temperature to achieve the proper wavelength and power level for single-line pumping at the D_0 line of helium at 1082.91 nm. The light level of the laser is monitored through the IR detector and the temperature of the laser is monitored by an internal thermistor, thus forming a closed-loop system. The control loop uses a signal produced by modulating the laser intensity at 9.5 kHz to produce a second harmonic signal at 19 kHz as the absorption signal is detected. The closed loop system continuously adjusts the laser temperature and current keeping the laser radiation at the correct wavelength for helium atom pumping.

In BFN vector mode, the sensor sweep and bias fields are generated by currents flowing in the Helmholtz three-axis coil system. The 864 Hz sweep signals are generated digitally in the control system and are multiplexed between the two transverse sensor axes x and y. A continuous sweep signal is digitally generated for the optical z axis and is phase shifted 90º. This forms the rotating sweep vector which modulates the absorption in the helium cell and is sensed by the IR detector. The bias field nulls the ambient field and the resulting coil currents provide measurements of the three vector components of the ambient magnetic field.

In scalar mode, the sweep and bias fields are removed and the laser is pulsed at the Larmor frequency (approximately 1.4 MHz in a 50,000 nT field) with a frequency modulation of 432 Hz. Selection of the OSP mode for the scalar measurements allows integration of a two-axis scalar mode with no additional hardware. The closed-loop bandwidth of the MVLM is 100 Hz with a sensitivity of 10 pT/√Hz in vector or scalar mode.

The calibration parameters of the vector magnetometer can be determined by the use of the scalar reference measurement which measures the magnitude of the magnetic field to an accuracy of better than 0.001%. Nine coefficients are required to calibrate the vector magnetometer. These consist of three offsets in the absence of a magnetic field, three scale factors for normalization of the axes, and three non-orthogonality angles which build up an orthogonal system intrinsically in the sensor. These coefficients can be determined by the scalar magnetometer reference and by exposing the vector instrument to an external magnetic field such as Earth's field. The instrument is turned into different directions relative to the magnetic field. The data set is a constrained minimization problem which can be solved by several established numerical procedures developed at Polatomic. These proven techniques allow the vector instrument to be calibrated to an absolute precision of ±1.0 nT.

Coordinate transformations are required to take into account the orientation of the spacecraft in inertial space and the internal rotations associated with the boom. One of the many advantages of the MVLM is the capability of measuring the vector components and scalar reference value in the same sensing volume. This eliminates orientation ambiguities and spatial gradients between the vector and reference magnetometers.

IV. SUMMARY

The Miniature Vector Laser Magnetometer (MVLM) provides stable three-axis vector measurements with ±1 nT accuracy over a dynamic range of ±100,000 nT and a sensitivity of 10 pT/√Hz. The MVLM utilizes single-line laser pumping of a helium cell sensing element and its operation is based on the principles of optically pumped He^4 in the metastable triplet state. The MVLM measures the vector components and scalar reference value in the same sensing volume. Vector measurements are made using the bias field nulling (BFN) technique and reference scalar measurements are obtained using the resonance technique of optically-driven spin precession (OSP). The design is configured for Earth science applications and can greatly reduce required spacecraft resources by replacing three fluxgate vector magnetometers and a reference scalar magnetometer with a single high performance instrument.

ACKNOWLEDGMENT

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